RESTORATION AND ENHANCEMENT OF TOMOSYNTHETIC IMAGES AND ITS APPLICATIONS IN DENTISTRY

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A shortcoming of conventional nonscreen dental radiographs is that anatomical overlay may obscure details of interest. Tomosynthesis provides some solution to this problem by producing images of slices through the object. However, Tomosynthesis does not only show the image of the slice of interest but also superposed blurred details of adjacent slices. Improvements can be achieved by high-pass filtering or iterative restoration. Best slice separation is obtained with complete high-pass filtering, but some anatomical structures may be more difficult to recognize. The techniques used in this study have a great potential for improving dental diagnosis.

INTRODUCTION

Conventional nonscreen dental radiographs render images which approach the limit of the information capacity available in existing x-ray technology. They offer images with a high resolution and a very small amount of quantum mottle. This makes the projection geometry of the radiograph often the limiting factor determining diagnostic performance. In most cases the appropriate projection angle can only be defined retrospectively after the picture has been obtained. Even then, by its nature, the radiographic projection results in an image that cannot provide information about the spatial relationship of structures in the direction of the x-ray beam. A technique that provides more information about the three-dimensional relationship of anatomical structures is tomography. Tomography permits the imaging of desired structures without the disturbing superposition of unwanted structures. A particular technique, known as <u>tomosynthesis</u>, permits the reconstruction of tomographic slices with desired orientation from a number of discrete radiographic projections obtained at different angles [1]. This investigation relates to the application of several filtering techniques and reconstruction methods, and their effect on the quality of the resulting tomosynthetic images representing dental structures.

Tomosynthesis

Tomosynthetic reconstruction is based on a set of radiographic images each taken from a different direction (fig. 1). A suitable choice for the different projections in dental applications are eight source positions located on a circular projection cone with opening half-angle of $\alpha = 4.5°$. This projection angle allows the reconstruction of slices with a thickness of about 3 mm for details of 0.5 mm [2]. Although tomosynthesis has some properties in common with computer assisted tomography (CT), the number of projections is much smaller (eight rather than hundreds) and the maximum angular disparity may be relatively small (about nine degrees instead of 180 degrees for CT). The component images each require a radiation dose of one eighth of the dose for a conventional dental radiograph, because

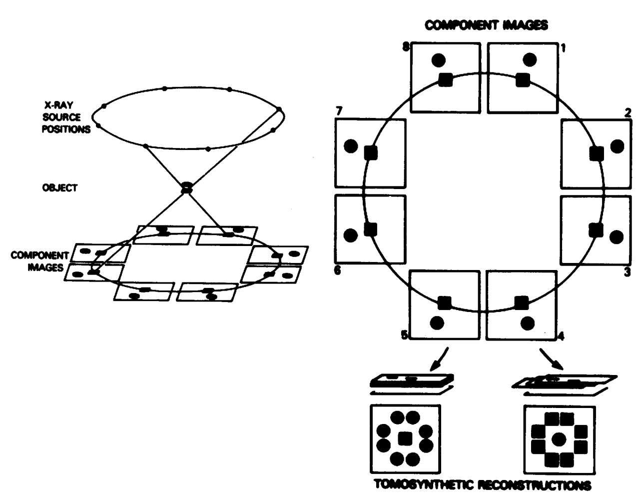

Fig. 1 The circular tomographic projection procedure.

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they are added to give the reconstructed image. Therefore, the dose to the patient in tomosynthesis is the same as with conventional radiography.
The synthesis is performed by adding the radiographic component images after proper positioning. This positioning determines the reconstruction plane. Shifting the component images in such a way that the projections of structures in the plane of interest coincide, results in a sharp reconstruction of the desired structures. Details outside the plane of interest will not coincide exactly and thus are blurred in the reconstruction. Other planes can be obtained similarly by varying the amount of relative shifts of the component images. The quality of the reconstruction is determined by the degree of blurring of unwanted structures lying in planes adjacent to the plane of interest.
The effective slice thickness depends on the projection angle α and the spatial frequency of characteristic details [2]. As a result large structures tend to "spill over" in adjacent slices more than smaller structures. Filtering out low frequencies can be a method to enhance the resulting reconstruction and to suppress blurred out-of-plane structures. Unfortunately such filtering techniques increase the relative amount of noise in the reconstructed image. A properly chosen high-pass filtering should suppress blur and add no more noise than is clinically acceptable.

Iterative Restoration

A special kind of high-pass filtering designed to improve the slice separation is iterative restoration [3], consisting in subtracting properly blurred images of adjacent planes from the plane of interest. The amount of blurring required is mathematically defined from the projection geometry of the component radiographs. This operation can be done for each image plane from a stack of planes covering the entire object of interest. The procedure can be iterated using the image planes restored at the previous step as input for further improvement of the restoration. At each iteration step a better cancellation of out-of-plane artifacts is obtained. It can be shown mathematically that this iteration process leads in the absence of noise to a complete deconvolution of the multiple planes [3]. In practice, the restoration process is stopped after the first few iterations because random noise and quantization artifacts preclude further improvements.

AIM OF THIS STUDY

It was shown that tomosynthesis can offer images of dental structures that give more information about the three-dimensional relationship of these structures than is achievable with conventional attenuation radiography [2]. This paper presents a comparison of some techniques aiming at the improvement of tomosynthetic images. They are the following:

1: high-pass filtering of the component images before tomosynthetic reconstruction;

2: iterative restoration of tomosynthetic slices;

3: the combination of these techniques.

The performance of these operations will be demonstrated with images of dental tissues.

MATERIALS AND METHODS

Radiographs

Conventional dental radiographs were obtained from the bicuspid region of a dry human mandible. For the tomosynthesis a set of eight radiographs was made according to a circular projection geometry with a half-angle of the projection cone of α = 4.5°. The effects of soft tissue scatter were simulated by a 2.5 cm thick slab of tissue equivalent material (Mix-D) placed in the x-ray beam just before the object. Posterior to the object, close to the film, thin metal cross bars were placed to enable proper alignment of the radiographs for digitization. The radiographs of a complete set of exposures were developed simultaneously.

Image Processing

Each of the eight radiographs was converted to a video signal and was digitized by an 8-bit analog-to-digital converter (256 grey levels) resulting in images of 512 x 512 pixels, corresponding to about 3 x 3 cm2 in the original image. A Gould IP 6400 Image Processor interfaced with a VAX 11/750 com-puter was used for the image processing.
The tomosynthetic slices were produced by properly shifting the digitized images with respect to each other and subsequent averaging. A total of 8 tomosynthetic planes covered the object and were used for further processing.
Discrete convolution kernels for high-pass filtering were selected to achieve a high-pass characteristic which is the mirror image of the blurring lowpass function between neighboring planes. One of these filters suppressed all DC-components of the image, (complete highpass), the other added 1/8 of the unfiltered image contrast to the high-pass filtered image. The image resulting

from the second filter has an appearance closer to that of a usual radiographic image (incomplete high-pass).
Iterative restoration was performed on the original reconstructions and on the reconstructions of the filtered component images. The restoration was performed using three or five planes simultaneously as described in the Introduction. Positivity constraints were applied at each iteration step to render the procedure robust in the presence of imaging noise [4]. The iteration process was terminated after four steps. After this number usually no further improvement of the visual quality can be expected. Contrast, resolution, and clinical relevance of depicted structures were criteria used for the quality assessment of the images. Separation between adjacent planes was measured by the correlation coefficient of the gray levels in pixels at the same xy-location.

RESULTS

Fig. 2 shows one of the component images and three tomosynthetic reconstructions from these component images. Tomosynthesis using the original components yields an image with blur that is characteristic for tomographic images. Slice separation is usually not sufficient for diagnostic purposes. The separation improves when high-pass filtered component images are used for the tomosynthesis.
Fig. 3 shows these images after incomplete high-pass filtering. Some of the original contrast is still present. The results for complete high-pass filtering are shown in figure 4.
Iterative restoration of tomosynthetic slices based on the original component images suppresses blur and gives more separation, especially the restoration based on 5 adjacent planes (fig. 5). The iterative restorations of the high-pass filtered versions of the images appeared to have too much noise to be clinically useful.
Table 1 shows the correlation coefficients between adjacent planes of three different mandibles for the various techniques.
These results confirm those based on the clinical evaluation of the images as shown before. Best slice separation is obtained by high-pass filtered tomosynthetic reconstruction. Iterative restoration of high-pass filtered tomosynthetic images also gives a rather low correlation coefficient, but the images are too noisy as mentioned before.

DISCUSSION

This study compares some techniques for the enhancement of tomosynthetic images, in terms of clinical usefulness and slice

Table 1 Correlation coefficients between adjacent planes. Mean and range for three different anatomical specimens

technique	correlation coefficient mean	correlation coefficient range
tomosynthesis:		
-original images	0.991	0.990 - 0.993
-incomplete high-pass filtered	0.895	0.895 - 0.895
-complete high-pass filtered	-0.092	-0.072 --0.112
iterative restoration:		
-original images, 3 slices	0.888	0.859 - 0.916
-original images, 5 slices	0.847	0.818 - 0.879
-incomplete high-pass, 5 slices	0.628	0.563 - 0.674
-complete high-pass, 5 slices	0.230	0.034 - 0.419

separation. The blurred appearance of the tomosynthetic images (Fig. 2) made from the original components is inherent in the tomographic method. The blurring mainly results from the spill-over of structures in adjacent planes. This can be seen by examining the mental foramen; although it is more clearly depicted in the buccal slice (Fig. 2d), it has not disappeared completely in the middle slice (Fig. 2c). The high-pass filtered versions give better results in this aspect. The high-pass filter that leaves a fraction of the lower frequencies in the image (Fig. 3) gives of course a less complete slice separation (Table 1). However, for certain diagnostic applications this method has advantages, e.g. for a first orientation about the spatial relationship in a certain anatomical area. In addition, complete filtering of lower frequencies proved to obscure to a certain extent desired structures in the plane of interest, too. Comparison of images in Figs. 3 and 4 reveals that the mental foramen is less clearly depicted in the completely high-pass filtered version of the restoration. Iterative restoration with 5 planes (Fig. 5c,d) gives more contrast than 3 plane iteration (Fig. 5a,b) and slightly better results than in-completely high-pass filtered tomosynthesis (Fig. 3b,d), but is computationally rather expensive.
The data from Table 1 confirm the conclusions of the clinical assessment. It is to be understood that the correlation coefficient merely summarizes the similarity

of two images, without separating the effects of anatomical structers and noise. Hence, while the correlation coefficients for the high-pass filtered iterative restorations indicate a good slice separation, clinical evaluation proved these images to be too noisy, and thus in this case the low correlation coefficient indicates the relative uncorrelatedness of the noise. Excluding the high-pass filtered iterative restorations from further consideration it is seen that completely high-pass filtered tomosynthesis gives best slice separation, followed by 5 plane iterative restoration.

CONCLUSIONS

It is obvious that tomosynthetic images need improvement by further image processing. Blurring and incomplete slice separation deteriorate the diagnostic usefulness of these images. Iterative restoration without high-pass filtering decreases the spill-over from neighboring planes and thus improves the slice separation drastically. The combination of high-pass filtering and iterative restoration applied to tomosynthesic images gives images that are too noisy to be useful. High-pass filtering combined with tomosynthesis significantly reduces the amount of blur. Complete high-pass filtering provides the best slice separation as shown by the correlation coefficient. Incomplete high-pass filtering provides an image quality and slice separation somewhat smaller than iterative restoration, however at a much smaller computational expense. Completely high-pass filtered images sometimes failed in depicting uniform details of large lateral extent as compared to images containing some low-pass information.

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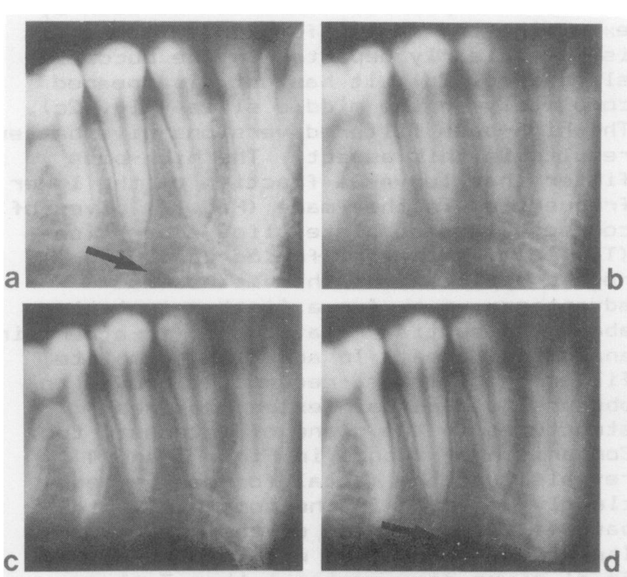

Fig. 2 Component image (a) and tomosynthetic images of three adjacent slices (b-d). (arrow:mental foramen)

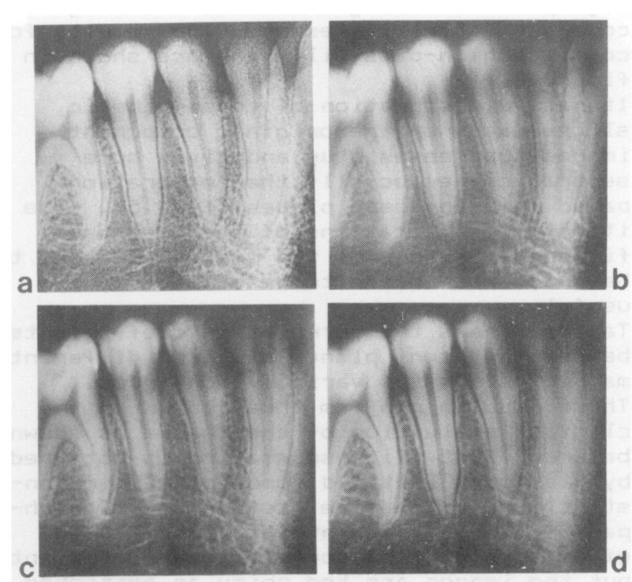

Fig. 3 Incompletely high-pass filtered component image (a) and tomosyntethic images of three adjacent slices (b-d).

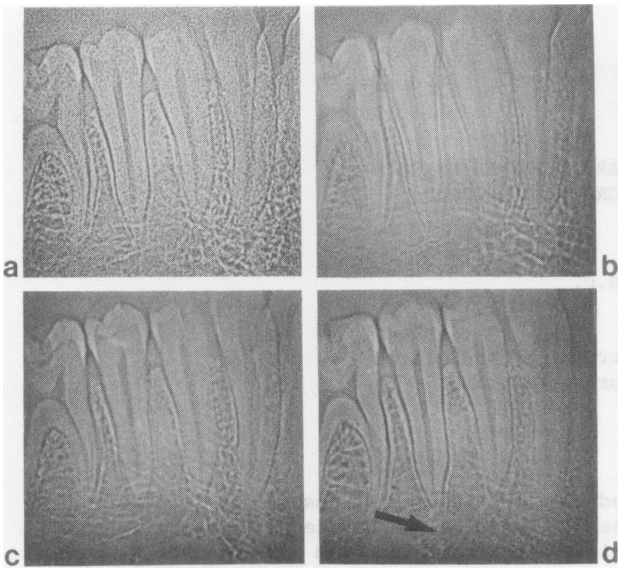

Fig. 4 Completely high-pass filtered component image (a) and tomosynthetic images of three adjacent slices (b-d).(arrow:mental foramen).

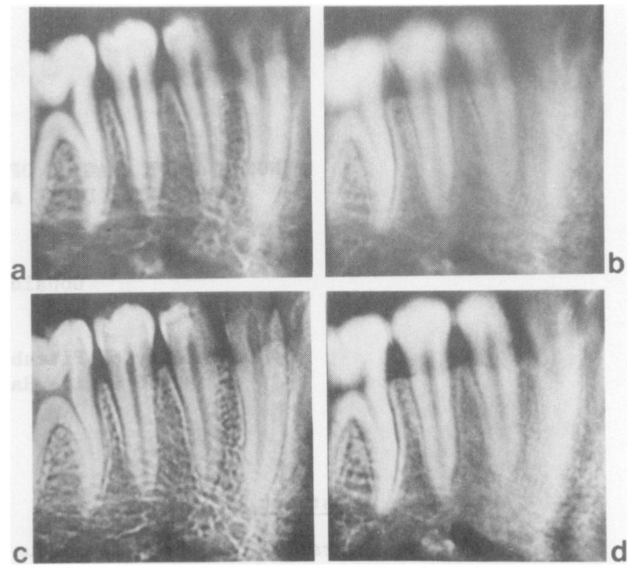

Fig. 5 Iterative restoration of two slices, based on three consecutive planes (a,b) and five consecutive planes (c,d).